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A puzzling millisecond pulsar companion in NGC 6266¹G. Cocozza^{2,3}, F. R. Ferraro², A. Possenti⁴, G. Beccari², B. Lanzoni², S. Ranson⁵, R. T. Rood⁶, N. D’Amico^{4,7}**ABSTRACT**

We report on the optical identification of the companion to the eclipsing millisecond pulsar PSR J1701–3006B in the globular cluster NGC 6266. A relatively bright star with an anomalous red colour and an optical variability (~ 0.2 mag) that nicely correlates with the orbital period of the pulsar (~ 0.144 days) has been found nearly coincident with the pulsar nominal position. This star is also found to lie within the error box position of an X-ray source detected by Chandra observations, thus supporting the hypothesis that some interaction is occurring between the pulsar wind and the gas streaming off the companion. Although the shape of the optical light curve is suggestive of a tidally deformed star which has nearly completely filled its Roche lobe, the luminosity ($\sim 1.9 L_{\odot}$) and the surface temperature (~ 6000 K) of the star, deduced from the observed magnitude and colours, would imply a stellar radius significantly larger than the Roche lobe radius. Possible explanations for this apparent inconsistency are discussed.

Subject headings: Globular clusters: individual (NGC 6266); stars: evolution – pulsars: individual (PSR J1701–3006B) – binaries: close.

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²Dipartimento di Astronomia Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy,

³INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy

⁴INAF, Osservatorio Astronomico di Cagliari, Loc. Poggio dei Pini, Strada 54, I-09012 Capoterra, Italy

⁵National Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA, 22903, USA

⁶Astronomy Department, University of Virginia, P.O. Box 400325, Charlottesville, VA, 22904, USA

⁷Dipartimento di Fisica Università di Cagliari, Cittadella Universitaria, I-09042 Monserrato, Italy

1. Introduction

NGC 6266 (M62) is one of the most massive and brightest ($M_V = -9.19$; Harris 1996¹) Galactic Globular Clusters (GCs), also is characterized by high values of the central density ($\log \rho_0 \sim 5.47$, with ρ_0 in units of $M_\odot \text{pc}^{-3}$; Beccari et al. 2006). It displays a King-model density profile with an extended core ($\sim 19''$) and a modest value of the concentration parameter ($c = 1.5$; Beccari et al. 2006).

Six binary millisecond pulsars (MSPs) have been discovered in M62 (D’Amico et al. 2001; Jacoby et al. 2002; Possenti et al. 2003, hereafter P03) and it ranks fifth of the GCs in wealth of MSPs, after Terzan 5, 47 Tucanae, M15 and M28². P03 presented phase-connected timing solutions, yielding precise celestial coordinates, for three of the MSPs in NGC 6266. One of them, PSR J1701–3006B (hereafter PSR 6266B) displays partial or total eclipses of the radio signal at 1.4 GHz near its superior conjunction (in the convection adopted throughout this paper, this corresponds to orbital phase $\phi = 0.25$), clearly due to gas streaming off the companion. The pulsar orbit is circular, with a projected semi-major axis of only $\sim 0.11 R_\odot$. P03 suggested two options for explaining the behaviour of the PSR 6266B system. The first option is that the pulsar companion is a non-degenerate bloated star, whose mass loss is sustained by ablation of its loosely bound surface layers by the relativistic wind emitted by the pulsar. In this case, PSR 6266B may resemble PSRs B1957+20 (Fruchter et al. 1990) and J2051–0827 (Stappers et al. 2001): the optical light curve of their companion star presents a maximum when the side of the companion facing the pulsar points toward the observer (i.e., at the pulsar inferior conjunction: $\phi = 0.75$). This is a clear signature of the irradiation of the companion surface by the pulsar flux. The second option has the pulsar companion as a tidally deformed star overflowing its Roche lobe due to the internal nuclear evolution. In this case, the system may be more like PSR J1740–5340 (D’Amico et al. 2001; Ferraro et al. 2001), where irradiation effects are negligible (Orosz & van Kerkwijk 2003) and the optical light curve of the companion is dominated by ellipsoidal variations (Ferraro et al. 2001), i.e. it shows two maxima at quadratures ($\phi = 0.0$ and 0.5).

We present the optical identification of the companion to PSR 6266B, based on high-quality phase-resolved photometry obtained with the *Hubble Space Telescope* (HST), and X-ray emission detected with *Chandra*.

¹Everywhere in this paper, we refer to the data at <http://www.physics.mcmaster.ca/Globular.html>

²See <http://www.naic.edu/~pfreire/GCpsr.html> for a catalog of MSPs in GCs with relative references

2. Observations and data analysis

HST OBSERVATIONS. The photometric data presented here consist of a set of high-resolution images obtained on August 1 2004 by using the Advanced Camera for Survey (ACS), on-board the HST, and retrieved from the *ESO/ST-ECF Science Archive*. The data comprise three R -band exposures (2×340 s and 1×30 s exposures), two B -band exposures (of 120 and 340 s) and four H_α -band exposures (of 340, 1050, 1125, 1095 s). The three longest exposures in H_α are the combination of three sub-exposures. An additional set of Wide Field Planetary Camera 2 (WFPC2, Prop. 10845, PI:Ferraro) data has been secured through the H_α filter with the specific aim of testing the possible variability of the companion: ten³ 1200 s exposures were taken between May 2 and May 5 2007. In order to best resolve stars in the most crowded regions, the Planetary Camera (with a resolution of $0.046''/\text{pixel}$) of the WFPC2 was pointed at the cluster center. The photometric analysis of the ACS dataset has been carried out using the ACS module of the Dolphot⁴ package (Dolphin 2000), using the FLT.fits datasets for the photometry, and the drizzled images as references for the geometric distortion correction. We set the photometry parameters as recommended in the Dolphot manual, obtaining a final catalog of B , R and H_α magnitudes, calibrated according to Sirianni et al. (2005). The final catalog is reported to an absolute astrometric system by cross-correlating the stars in common with the data set of Beccari et al. (2006), which has been astrometrized by using the standard stars from the new *Guide Star Catalog II (GSCII)* lying in the considered field of view (FoV). At the end of the procedure, the rms residuals were of the order of $\sim 0.5''$ both in RA and Dec; we assume this value as representative of the astrometric accuracy.

In order to carefully search for any variability from the MSP companion, we reanalyzed the H_α images in a small area around the nominal position of PSR 6266B by using ROMAFOT (Buonanno et al. 1983). This package has been specifically developed to perform accurate photometry in crowded fields, and it also allows a visual inspection of the quality of the PSF-fitting procedure. In particular, we extracted 50×50 -pixels ($\sim 2.5'' \times 2.5''$) sub-images from the ten original H_α ACS frames, each centered on the nominal position of PSR 6266B. In order to optimize the detection of faint objects, we performed the search procedure on the median image. Then, we adopted the resulting mask with the star positions to the individual sub-images, and performed the PSF-fitting procedure separately on each of them. We adopted the same strategy for the analysis of the nine WFPC2 H_α images,

³Only 9 exposures have been used in the analysis since one was made useless by a cosmic ray passage.

⁴The DOLPHOT packages, including the ACS module and all the documentation, can be found at <http://purcell.as.arizona.edu/dolphot/>.

after the careful alignment with the previously astrometrized ACS frames. The resulting instrumental magnitudes were transformed to a common system, and we compiled a final catalog with coordinates and magnitudes for all the stars identified in the considered 19 sub-images. The photometric calibration of the instrumental magnitudes and the absolute celestial coordinates were determined by using all the stars in common with the overall ACS catalog, calibrated and astrometrized as discussed above.

CHANDRA OBSERVATIONS. NGC 6266 was observed for 63 ks on May 2002 with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS). The ACIS-S3 chip was pointed at the cluster center, its FoV ($8' \times 8'$) entirely covering the half-mass radius ($1.23'$; Harris 1996). The data were reduced using the CIAO software (v. 3.3.0), reprocessing the level 1 event files; the task `acis_run_hotpix` was used to generate a new badpixel file. Then we applied the corrections for pixels randomization, good time intervals and grades. Our analysis includes only photons with ASCA grades of 0, 2, 3, 4 and 6. About 1.5 ks of observations were not considered in the analysis because of the high background level. We searched for discrete sources in our level 2 event file using `Wavdetect` (Freeman et al. 2002), performing the source detection separately on the 0.2-1, 1-2, 2-8, and 0.2-8 keV bands. The detection threshold was set to 10^{-5} , and the source detection was performed increasing the sequence of wavelets from 1 to 16 by factors of $\sqrt{2}$. More than 110 sources were detected in the 0.2-8 keV band in the entire chip. The astrometry of all the detected sources was corrected by using the Aspect Calculator provided by the *Chandra* X-Ray Center. Then we searched for possible optical counterparts both in our HST images and catalog. About 5 bright stars and 2 faint and extended objects (likely background galaxies) were found to coincide with the X-ray sources well outside the half-mass radius, where the stellar density is relatively low. We therefore used these optical counterparts for extending the astrometric solution of HST to the *Chandra* sources, thus obtaining the same accuracy in the absolute astrometry for both the optical and the X-ray sources.

3. Results

Figure 1 shows the $3'' \times 3''$ WFPC2 H_α map centered on the PSR 6266B nominal position (marked with a *cross*), as derived from timing (see P03). An accurate photometric analysis has been carried out for all the ~ 30 stars found in our catalog within a distance of $1.5''$ from the PSR 6266B position. This correspond to 3 times the 1σ uncertainty ($0.5''$) in the absolute astrometry of the HST data. In particular, we have extracted 19 individual images from our dataset (10 exposures with ACS and 9 with WFPC2) and compared the resulting magnitudes for each object in order to search for variability and estimate the typical

photometric uncertainties at different magnitude levels. Only one source in the catalog (hereafter named COM 6266B, marked with a small circle in Fig. 1) showed H_α variability ($\Delta H_\alpha \sim 0.2$ mag) significantly larger than the typical rms magnitude fluctuations of stars of similar luminosity ($\delta H_\alpha \sim 0.02$ mag in ACS data, and $\delta H_\alpha \sim 0.04$ mag in WFPC2 data). Its celestial coordinates are $\alpha_{J2000} = 17^h01^m12^s.690$ and $\delta_{J2000} = -30^\circ06'48''.61$, whereas the mean apparent magnitudes are $B = 20.58$, $V = 19.48$, $R = 19.02$, $H_\alpha = 18.65$ (V is from Beccari et al. 2006). It is located at $0.5''$ from PSR 6266B just at the edge of its positional error circle.

Figure 2 reports the $(R, H_\alpha - R)$ and $(R, B - R)$ Color Magnitude Diagrams (CMDs) for all the stars detected in the $20'' \times 20''$ box centered on the PSR 6266B nominal position. COM 6266B is marked with a *large filled triangle* in both the CMDs. As apparent from the figure, the star has almost the same luminosity of the cluster Turn Off, but it shows an anomalous red color which locates it out of the Main Sequence. The photometric properties imply that it is not a degenerate star and that it has a moderate H_α excess, indicating the presence of ionized gas surrounding the system. These findings are consistent with the irregularities seen in the radio signal of PSR 6266B and supports the scenario that COM 6266B is a mass losing star.

In order to firmly assess the physical connection between COM 6266B and the binary pulsar PSR 6266B, we have accurately investigated the time scale of the optical variability⁵ (in the 0-1 day range). The H_α time series (19 points) was processed using the GRATIS χ^2 fitting routine, a code developed at the Bologna Astronomical Observatory in order to study the periodicity of variable stars (see, e.g., Clementini et al. 2000). Following the procedure fully described in Ferraro et al. (2001), the most significant (99% confidence interval)⁶ periodicity was found at a period of 0.1446 ± 0.0015 day, consistent, within the uncertainties, with the orbital period of PSR 6266B derived from timing ($P_b = 0.1445454303(6)$ day, where the figure in parenthesis is the uncertainty, at 99% confidence level, on the last quoted digit; P03). Given that, we have folded the 19 magnitude values, by using P_b and the reference epoch of the PSR 6266B radio ephemeris ($T_0 = 52047.258199(2)$; P03). The results are shown in Fig.3. As apparent, the ACS and the WFPC2 data (obtained about 3 years later)

⁵Note that COM 6266B has a close companion located at only 4 pixels ($\sim 0''.19$) West in the ACS map (see Fig.1). This object turns out to be a normal Sub-Giant Branch star, slightly brighter (~ 0.5 mag in B , R and H_α) than COM 6266B and not displaying any evidence of variability. Although very close to each other, the two stars are clearly separable in the high resolution ACS and WFPC2 images and we have verified that the photometric analysis of COM 6266B is not affected by the presence of this close star.

⁶The significance level has been obtained from the reduced χ^2 of the Fourier time series fit (at different modulation periods) to the H_α data (see for example Figure 2 of Ferraro et al. 2001).

agree with each other, drawing a well defined light curve with two distinct maxima at about $\phi = 0.0$ and $\phi = 0.5$. This fact, as well as the phases and the amplitudes of the minima, confirms that the optical modulation is associated with the pulsar binary motion and strongly suggests that COM 6266B is a deformed star overflowing its Roche lobe (see §1).

Additional properties of this system can be derived from the analysis of the *Chandra* data. We found an X-ray source located at only $\sim 0''.4$ from COM 6266B and at $0''.3$ from the nominal radio position of PSR 6266B. The derived coordinates of the X-ray source are $\alpha_{J2000} = 17^{\text{h}}01^{\text{m}}12^{\text{s}}.700$ and $\delta_{J2000} = -30^{\circ}06'49''.08$, and the 1σ uncertainty area on its position is encircled in Fig.1 (dashed line). Given the number of sources (50) detected within the half-mass radius of NGC 6266, the probability of a chance superposition of a X-ray source within $0''.3$ from the radio position of PSR 6266B is $\sim 7 \times 10^{-4}$, strongly supporting the association of the detected source with the PSR 6266B system. The (background subtracted) photons counts are $18.3^{+5.3}_{-4.2}$ (soft: 0.2–1 keV), $23.7^{+6.0}_{-4.9}$ (medium: 1–2 keV) and $9.8^{+4.3}_{-3.1}$ (hard: 2–8 keV), implying $\text{HR1} \simeq 1.3$ and $\text{HR2} \simeq 0.4$ (where $\text{HR1} = \text{medium}/\text{soft}$ counts and $\text{HR2} = \text{hard}/\text{medium}$ counts). Hence the source is harder than the typical MSP population observed in GCs (e.g. Grindlay et al. 2002) and the HR1, HR2 values resemble those of a source in which the pulsar wind shocks the material released from the companion (see, e.g., the cases of PSR J1740–5340 in NGC 6397, and PSR J0024–7204W in 47Tuc; Grindlay et al. 2002, and Bogdanov et al. 2005, respectively). Even if the small number of photons prevents a detailed spectral analysis, for an absorption column density $N_H = 2.2 \times 10^{21} \text{ cm}^{-2}$ (Pooley et al. 2003), the counts in each band and the HR1 and HR2 values are consistent⁷ with a power law model having a photon index $\simeq 2.5$, and a total unabsorbed flux $F_X \sim 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.2–8 keV band, translating (for a distance of 6.6 kpc; Beccari et al. 2006) into a X-ray luminosity of $L_X \sim 6 \times 10^{31} \text{ erg s}^{-1}$.

4. Discussion

Many observed features of COM 6266B (namely, its anomalous red colour, the H_α excess, the shape of the light curve, the X-ray emission from the binary) are suggestive of a tidally deformed star which is experiencing heavy mass loss, similar to the system found in NGC 6397 by Ferraro et al. (2001). On the other hand, other photometric properties of the source do not fit this picture, as described below.

By assuming the reddening $E(B - V) \sim 0.47$ and the distance quoted by Beccari et al. (2006), and adopting $[Fe/H] = -1.1$ and an age of 12 Gyr for NGC 6266, we have determined

⁷The PIMMS tool has been used for these estimates: <http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html>

the physical parameters of COM 6266B from the comparison of its position on the CMDs (Fig. 2) with the isochrones of Pietrinferni et al. (2004). The resulting effective temperature, bolometric luminosity and radius of this star are $T_{\text{eff}} \sim 6000 \pm 500 \text{ K}$, $L_{\text{bol}} \sim 1.9 \pm 0.2 L_{\odot}$, and $R \sim 1.2 \pm 0.2 R_{\odot}$, respectively, where the quoted uncertainties are conservative estimates, essentially due to the uncertainties in the distance modulus ($\pm 0.15 \text{ mag}$) and in the reddening ($\pm 0.05 \text{ mag}$). If the luminosity variations shown in Fig. 3 are mainly due to tidal deformations of the companion star, the stellar radius R is expected to be of the order of the Roche lobe radius R_L . The latter can be estimated from the mass function and the projected semi-major axis of PSR 6266B (derived from pulsar timing; P03), provided that a pulsar mass M_{psr} and an orbital inclination i are assumed. As already discussed in P03, the presence of radio eclipses indicates that i is not small. Conservatively taking $i \gtrsim 20^\circ$ and assuming $M_{\text{psr}} = 1.4 M_{\odot}$, the companion star is expected to span a mass interval ranging from $0.125 M_{\odot}$ ($i = 90^\circ$) to $0.41 M_{\odot}$ ($i = 20^\circ$)⁸, corresponding to $R_L \sim 0.26 R_{\odot}$ and $0.40 R_{\odot}$, respectively. The value of R_L is only slightly affected by the choice of M_{psr} , being, for instance, $R_L \lesssim 0.45 R_{\odot}$ for $0.7 M_{\odot} \leq M_{\text{psr}} \leq 3.0 M_{\odot}$ (a safely large neutron star mass range; see, e.g., Freire et al. 2008). Note that in order to match the estimated R_L with the observed R it should be $i \sim 3^\circ$ (for $M_{\text{psr}} = 1.4 M_{\odot}$), thus implying an unreliable companion mass of $\sim 6 M_{\odot}$. In summary, for all plausible binary parameters, it turns out that the observed stellar radius of COM 6266B is significantly larger ($R \gtrsim 3 R_L$) than the expected Roche lobe radius of the companion to PSR 6266B, i.e. COM 6266B appears $\gtrsim 10$ times brighter than the expected luminosity of any pulsar companion having an effective temperature $T_e = 6000 \text{ K}$.

Under the hypothesis that COM 6266B is the companion to PSR 6266B, what is the origin of this remarkable discrepancy? A number of possibilities are examined below.

(i) The binary system could not belong to the cluster. In this case the adopted distance would be inappropriate and the value of the radius deduced from the luminosity would be largely overestimated. On the other hand, the celestial position of PSR 6266B is at less than $2''$ from the cluster center, and the pulsar shows a negative value of the spin period derivative, as expected if PSR 6266B lies in the cluster potential well.

(ii) The optical luminosity of COM 6266B could be dominated by strong non-thermal processes, possibly triggered by the pulsar spin down power $L_{\text{sd}} \lesssim 10 L_{\odot}$ (see P03). Also in this case the value of the stellar radius deduced from the observed luminosity could be significantly overestimated. However, At the orbital separation of $1.4 R_{\odot}$, the energy captured by a Roche lobe filling companion would be of the order of $L \sim 0.1 - 0.2 L_{\odot}$ which

⁸Note that in both cases the orbital separation of the system turns out to be $a \sim 1.4 R_{\odot}$.

is too low to explain the observed value. Moreover, it is hard to explain how a large non-thermal component may generate a light curve with maxima that fall at orbital phases nicely consistent with those expected for light curves modulated by ellipsoidal variations.

(iii) COM6266B could be the blend of two low-luminosity stars: one star would be the optically variable companion to PSR 6266B and the other one a non-variable star in the foreground (background). While stellar blends are not uncommon in the highly crowded GC cores, this possibility only partially alleviates the problem. In fact, by assuming that COM6266B is the blend of two stars of equal mean H_α magnitude (i.e., $H_\alpha = 19.35$), the observed ellipsoidal modulation could only be produced if the pulsar companion varies by $\Delta H_\alpha \sim 0.35$ mag, which is a rather extreme value for variabilities induced by tidal distortions. Moreover, even in this case, the star would have a radius $R \gtrsim 1.7R_L$. Matching R with R_L would require that COM6266B is e.g. the blend of a non-variable star with $H_\alpha = 18.7$ and a star with mean magnitude $H_\alpha \sim 21$ varying by $\Delta H_\alpha > 3$ mag. We note that similar considerations would apply also if PSR 6266B were a triple system.

In conclusion, while option (iii) seems to be a quite unlike *ad hoc* scenario, options (i) and (ii) will be finally addressed as soon as spectroscopic data are available for the system. This will allow us to investigate the nature (thermal or not thermal) of the optical emission and the association of the source to the cluster (via the determination of the radial velocity), hence shedding some light on the nature of this puzzling object.

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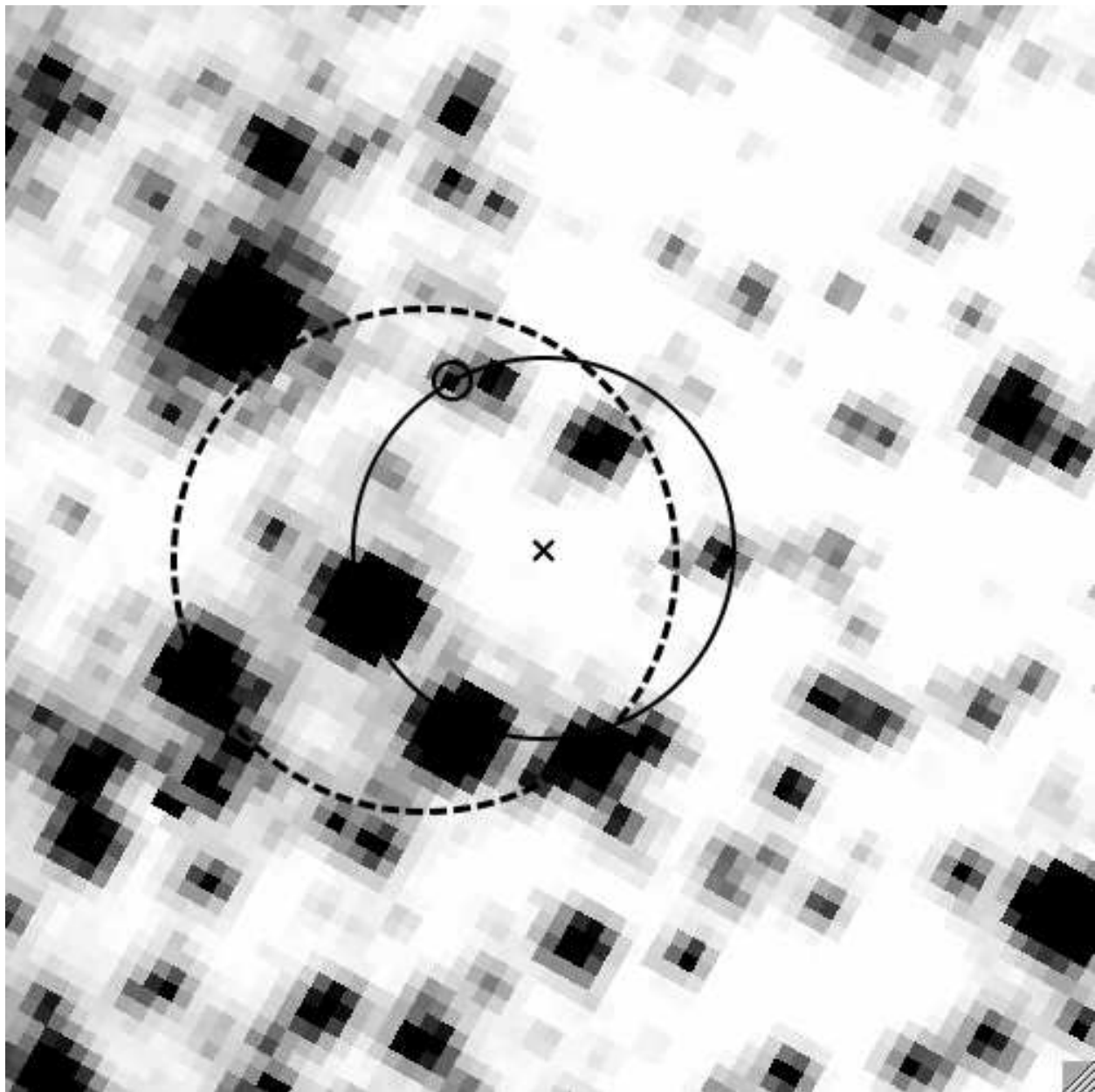


Fig. 1.— Finding chart for COM J1701–3006B showing the median-combined WFPC2 H_α image. The region covers $3'' \times 3''$; the cross marks the nominal position of PSR 6266B, with the 1σ error circle ($0.5''$, solid line). The smaller circle shows the optical counterpart, whereas the dashed line represents the 1σ circle ($0.7''$) in the *Chandra* position. North is up and East is to the left.

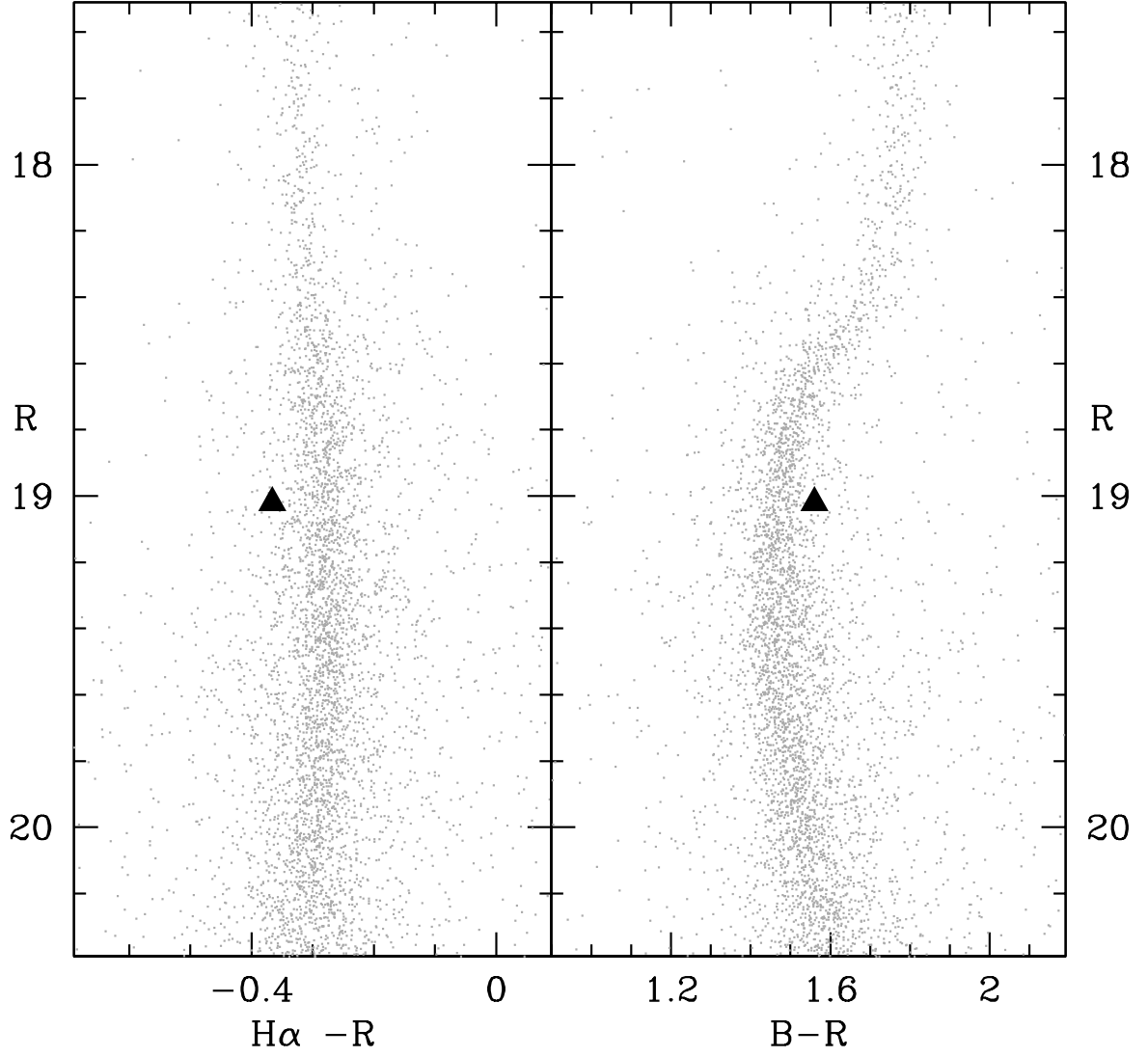


Fig. 2.— $(R, H_{\alpha} - R)$ and $(R, B - R)$ CMDs for stars identified in a region of $20'' \times 20''$ centered at the nominal position of PSR 6266B. The optical counterpart to the pulsar companion COM 6266B is marked with a *large filled triangle*.

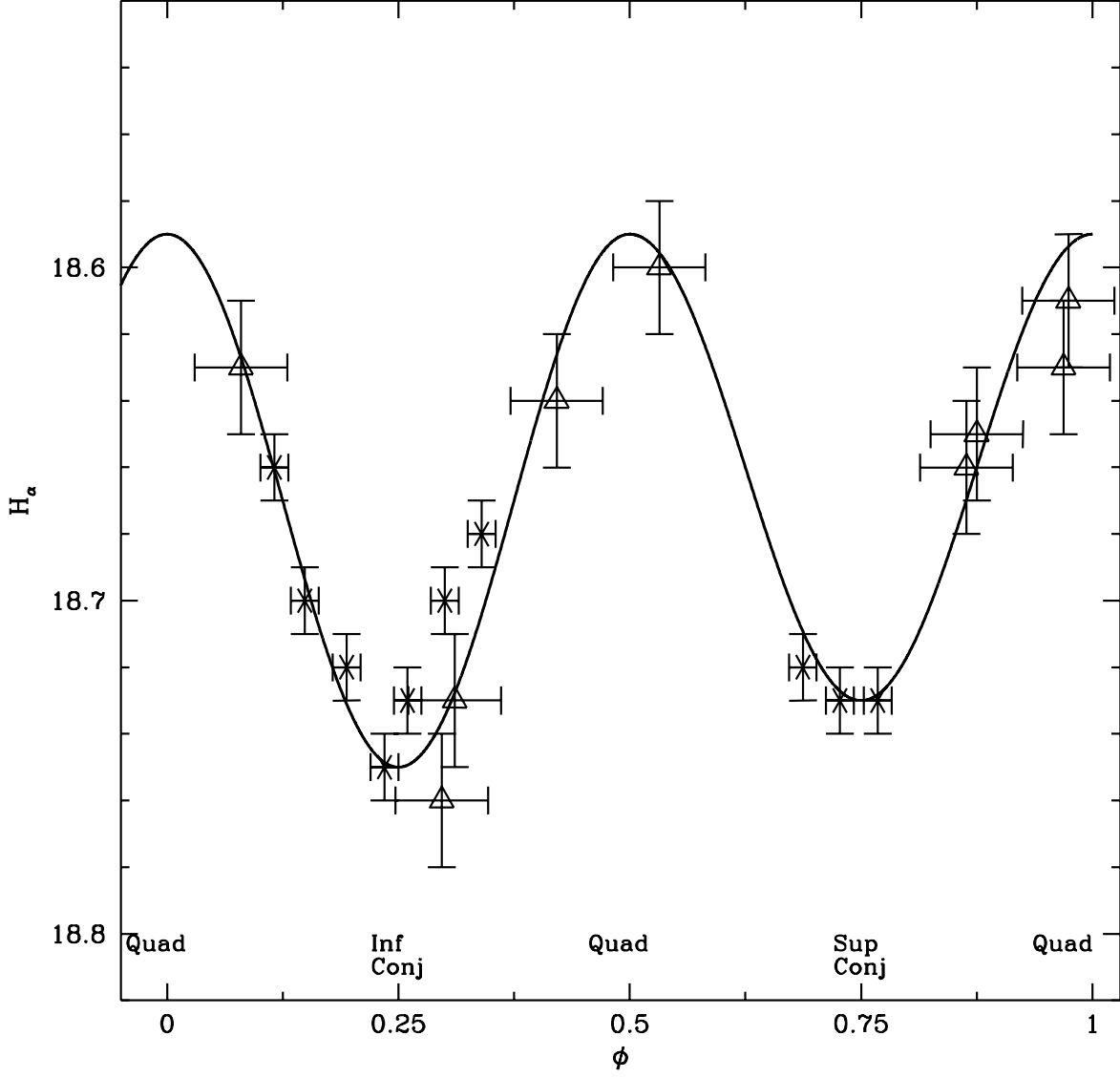


Fig. 3.— H_α light curve of COM6266B obtained by using the period and the reference epoch of the radio ephemeris of PSR 6266B. Asterisks represent ACS archive observations performed in August 2004; large empty triangles are the WFC2 data collected in May 2007. The phases of quadrature and conjunction of COM6266B are reported for clarity. The *solid line* represents the Fourier time series (truncated to the second harmonic) that best fits the data.